

Optical systems for free-space laser communications

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ABSTRACT

An overview of optical systems utilized in JPL's Optical Communications research is provided here. These include discussions on the flight terminal optics, the ground receiver aperture and the uplink beacon or command optical system. On-going efforts on these and beam-coupling techniques will be described.

Keywords: telescope, flight optics, photon buckets and optical communications

1. INTRODUCTION

Laser-communications to and from airborne and space-borne assets typically involves there differing optical systems with widely different requirements. These include the flight terminal with typical telescope apertures on the order of 5 to 50 cm in diameter, the ground receiver terminal with apertures on the order of 0.5 to 10 m, and the uplink command or optical beam pointer (e.g. beacon) with aperture diameters on the order of 0.5 to 1 m. Ongoing efforts at JPL on each of these areas are briefly described here. The flight terminal's optical train can accommodate transmit, receive, align (calibration), and beacon reference channels for acquisition, tracking and pointing. The optical system consists of a front aperture (reflection or refraction type telescope), optics (lenses, mirrors, beam-splitters, and filters), fast-steering mirror(s), and acquisition and tracking detector(s).¹⁻³

2. FLIGHT TERMINAL REQUIREMENTS AND DESIGN DRIVERS

Some of the design drivers and design practices for a flight terminal are tabulated below:

Design Driver	Justification
Compact telescope length	The requirement for short telescope length limits the F/# of the telescope primary mirror to about F/1.0.
Afocal telescope	A collimated path affords design simplifications, for example, to accommodate a fine-pointing mirror.
Field-of-view (FOV)	FOV requirement of a fraction of a degree (for acquisition and beam steering) is relatively large for two-mirror telescope optical systems.
Stops	A field-stop can effectively block the light from bright objects (like the Sun) near the edge of the field of view in the telescope. A Lyot stop can largely eliminate diffracted energy from bright out-of-field objects.
Background light rejection	Rays directed around the baffles to anywhere inside the field-stop must be blocked-off before going through the telescope aft optics.
Stability	A level of stability, typically on the order of 0.2 μ rad, must be maintained between the transmit and the receive channels.
Polarization	The polarization state of the transmitter is of interest for rejection of unpolarized background light
Spectral width	The telescope may have to accommodate both the beacon and the transmit wavelengths, difficult to achieve without use of reflective optics.
Redundancy	The numerous beam-splitters required make the auxiliary optical path length long, increasing overall volume.
Environment	The radiation environment becomes a design consideration, mainly for the refractive optics and some of the dielectric coatings within the system.

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3. OPTICAL CHANNELS

Commonly used optical channels are: Transmit; Receive; Acquisition and Tracking (e.g. beacon); and Reference (or align). The optical system transmits optical data and receives beacon signals. The transmit and receive channels may consist of separate or common apertures. The beacon signal is used for acquisition and tracking and the uplink command data from Earth or from another spacecraft. The beacon signal might be narrow band, such as a laser signal from a cooperative target, or wider spectrum sources such as celestial reference signals from stars, or a Sun-illuminated Earth or moon. The different optical channels are described here briefly. The Transmit Channel consists of an optical path extending from the output of the laser transmitter to the exit aperture of the optics. The Receive Channel's function is to accept light emerging from the fore-optics, and direct it to a photo-detector. The Acquisition and Tracking Channel images the incoming beacon signal onto the acquisition and tracking detector. Reference (or align) Channel forms an image of a portion of the transmit light at the array detector without requiring any high degree of image quality.

Transmit /Receive Isolation: Since the transmit power is typically ten orders of magnitude larger than the receiver sensitivity levels, as much as 150 dB isolation of the receive channel from the transmit channel may be required for a given transceiver that must point near the Sun. Scattering from optical surfaces have to be kept to a minimum and adequate optical isolation must be built in at each stage of the design. Different isolation schemes can be implemented and include: spatial isolation; spectral isolation (e.g. filtration); temporal isolation (e.g. transmitting and receiving at different times); polarization isolation; aperture sharing; coding that utilizes codes with extreme depth of interleave; and combined Isolation.

Dedicated Star-Trackers: One or more dedicated star-trackers may be added to the optical system as the acquisition and tracking beacon. Since knowledge of alignment between these sensors and the optical channels within terminal is extremely critical (for sub-micro-radian pointing) the star tracker(s) need to be an integral part of the optical system. A dedicated star tracker will have a small aperture on the order of 6 to 8 cm, but with much wider field-of-view (a few degrees).

Mechanical, Thermal, and Temporal Stability: Structural integrity and thermal stability of the terminal are critical parameters of the design. At the same time, the telescope mass should be kept as low as possible. Thermal gradients may alter the surface figure of the optical system, as can mismatch between the thermal expansion of optics and the structure of the optics. Figure (1) shows the picture of an all SiC telescope that was manufactured by SSG Inc. for JPL. This lightweight (< 6 kg) 30-cm diameter telescope showed optical alignment stability over a temperature range of $\pm 50^\circ \text{C}$.⁴⁻⁵

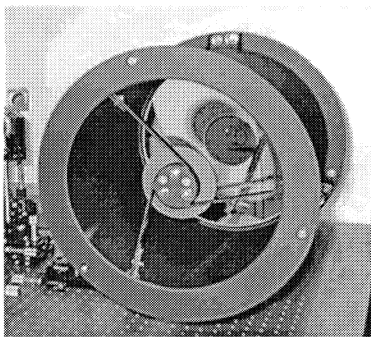


Figure 1. A lightweight, 30-cm all SiC telescope with spherical primary mirror

4. OPTICAL DESIGN APPROACHES

Both reflective and refractive type telescopes, in an on-axis or off-axis arrangement, may be used for the flight terminal. Of these, the refractive and off-axis telescopes are often bulkier. Off-axis telescopes require higher degree of alignment, but, provide a larger field-of-view. Figure (2) shows the schematic of a doubly redundant laser transmitter configuration designed at JPL.

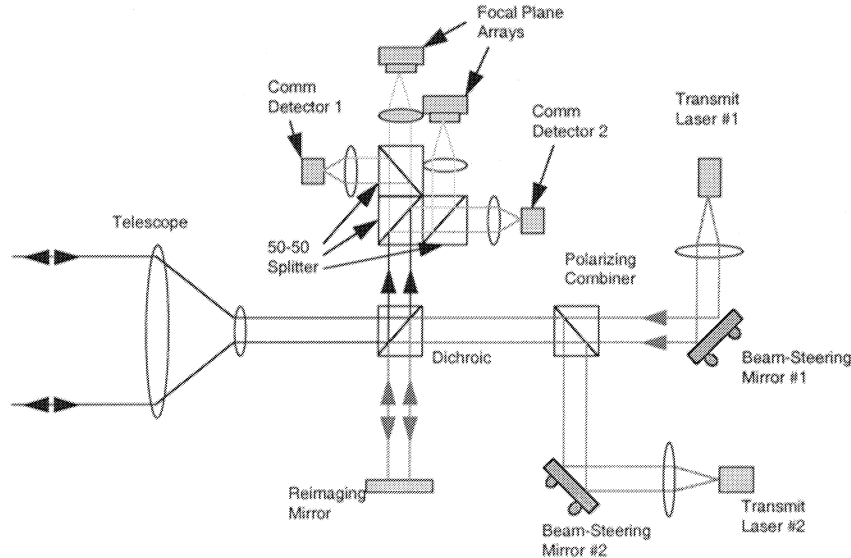


Figure 2. Block diagram of the optical communication transceiver including redundant subsystems

Figure (3) shows the picture of a JPL laser-communication terminal, called OCD (Optical Communication Demonstrator) that uses the architecture shown in Figure (2) above, but in a single-string (no redundant channels) configuration.

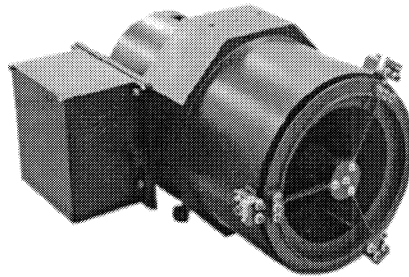


Figure 3. The OCD flight terminal prototype

5. GROUND TERMINAL

A 1-meter diameter telescope dedicated to optical communications has recently been designed and built. This terminal, called OCTL (optical Communication telescope Laboratory) is an R&D station for optical communication with primarily near-Earth missions and possibly close-range deep-space missions. OCTL is capable of tracking LEO and GEO spacecrafts. This telescope may also be utilized for transmitting beacon or command signals to a spacecraft. A picture of the OCTL telescope is shown in Figure (4)

Some of the top-level optical requirements for the OCTL telescope include: Low optical throughput losses (~70% transmission at wavelengths > 500 nm); a coude optical path, support for high power laser transmission; operability as close as 30° from the Sun; encircled energy >66% and >80% in 1.54 μrad and 2.81 μrad (Airy disk), respectively.

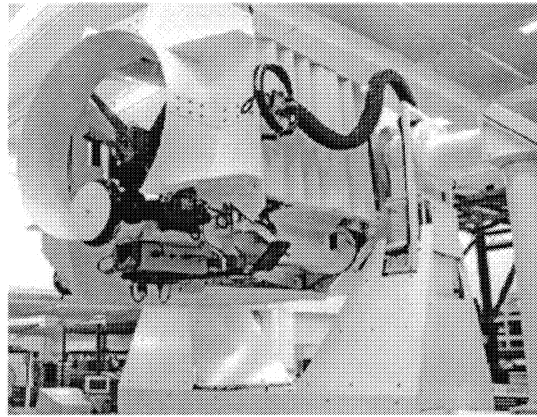


Figure 4. Picture of the 1-m telescope dedicated to laser-communications

A daytime Adaptive Optics (AO) system is under development, to be tested initially with the OCTL telescope. A block diagram of the test bed for the AO system is shown in Figure (5). AO systems typically utilize natural and/or laser guide stars to correct the atmospheric turbulence induced wave front aberration. The JPL approach utilizes the intensity distribution of the aberrated wave front detected on an array of communications detectors for feedback to the deformable mirror. An AO system that achieves 95% Strehl corresponds to a wavefront error of $\lambda/20$ at 1000-nm and 80% of the energy encircled in a 4- μ rad blur circle diameter. Achieving this level of performance under the worst-case background conditions will require an actuated mirror with 900 actuators per square meter of aperture. A 97 actuated-mirror system is being constructed for the AO test bed correcting to $\lambda/7$ wave front error. About 80% of the energy will be enclosed in a 12- μ rad diameter spot. The larger focused spot will result in an order of magnitude increase in background noise at the receiver.

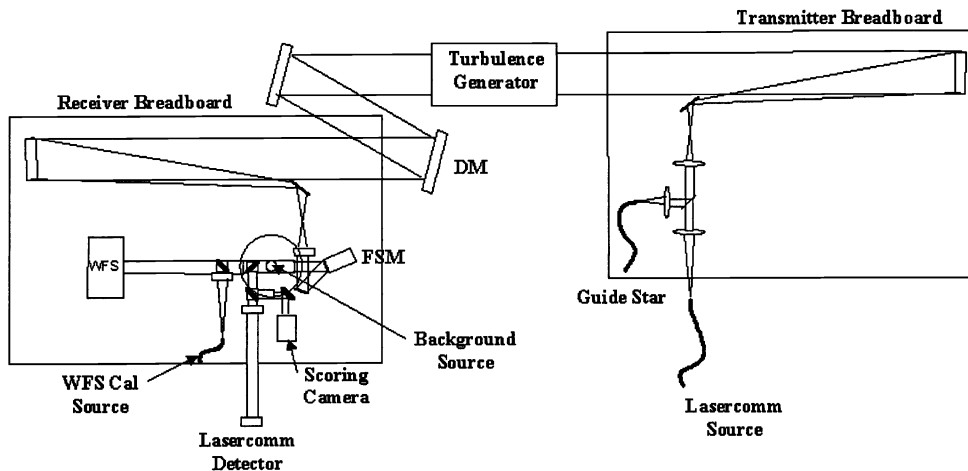


Figure 5. Schematic of the daytime Adaptive Optic testbed

Large aperture optical receivers are of primary interest for deep-space Optical Communication ground reception. Since photon collection, rather than imaging, is of main interest, the telescopes could be of non-diffraction-limited quality. However, the telescope has to be able to focus the beam to a diameter of about 2-mm. This corresponds to the active diameter of the photon-counting detectors that are being considered as part of the opto-electronic receiver.

Single large apertures having monolithic or segmented primary mirrors, and arrays of small (on the order of 1-m diameter) telescopes are being considered. For the single large aperture, a viable and potentially low-cost candidate is a spherical primary with 10x10 array of 1-m spherical panels. Figure (6) shows this concept schematically.

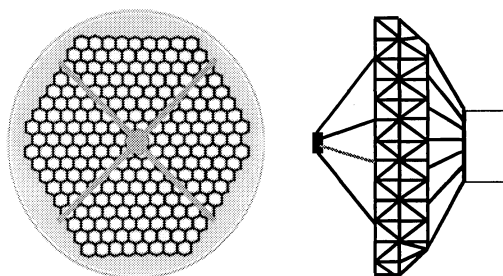


Figure 6. Schematic of the segmented mirror with 10-meter primary

Optical schemes that reduce spherical aberration of the all-spherical primary mirror to provide tighter focusing of the beam from a non-diffraction limited quality telescope are also being studied. One option is clamshell focusing arrangement as shown in Figure (7).

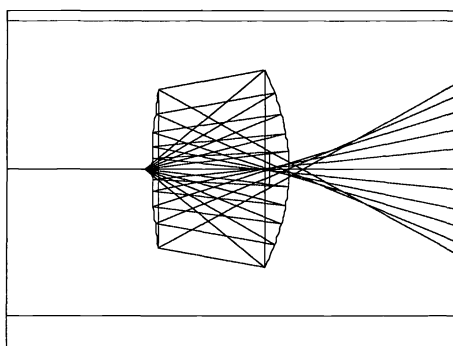


Figure 7. Schematic of the clamshell optical system for tighter focusing of the received beam. The input light reflected from a spherical primary mirror enters from the right and the detector is located at the left hand side of the Figure.

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